A Prognostic Development Methodology with Demonstration Examples

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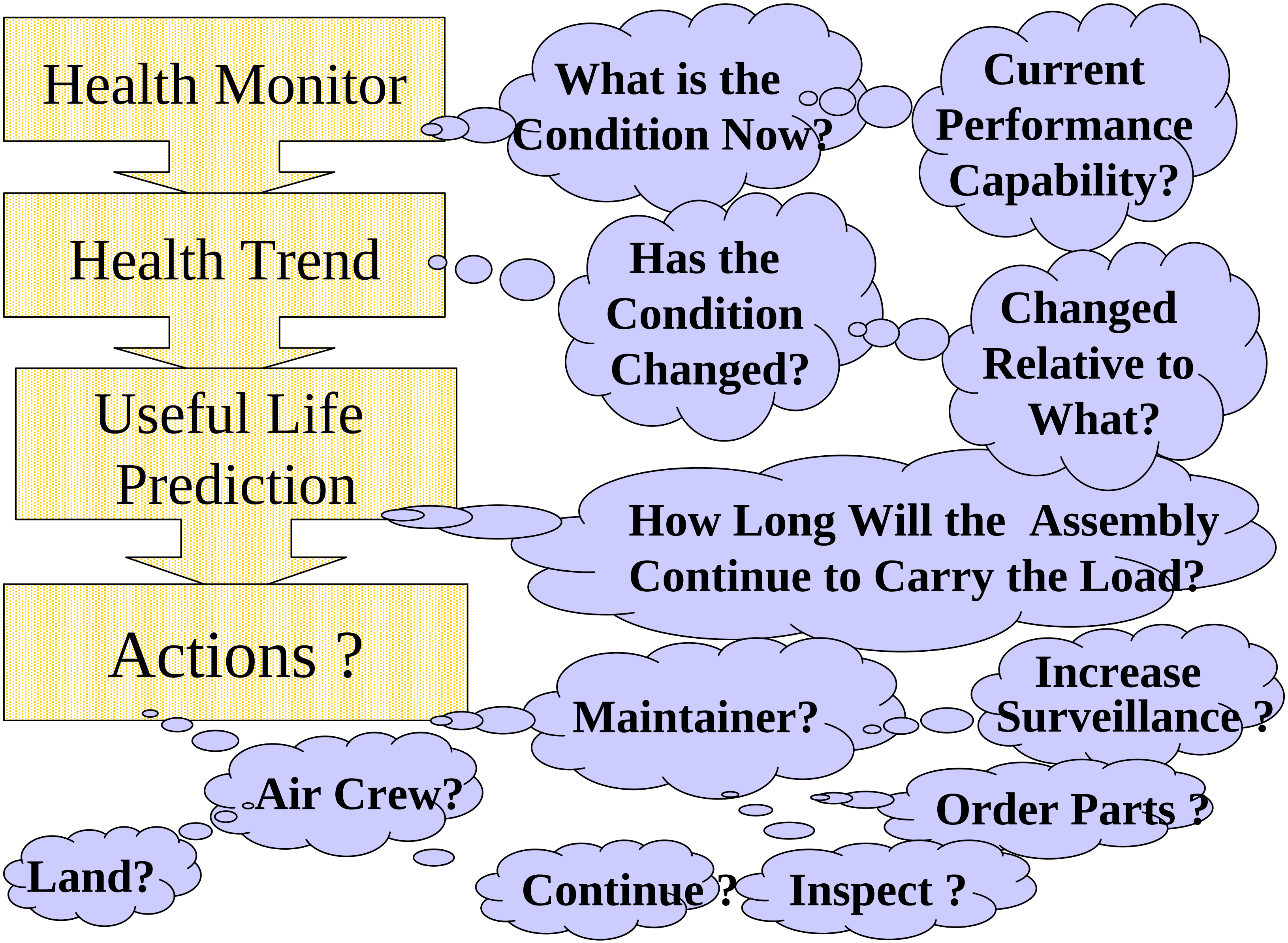
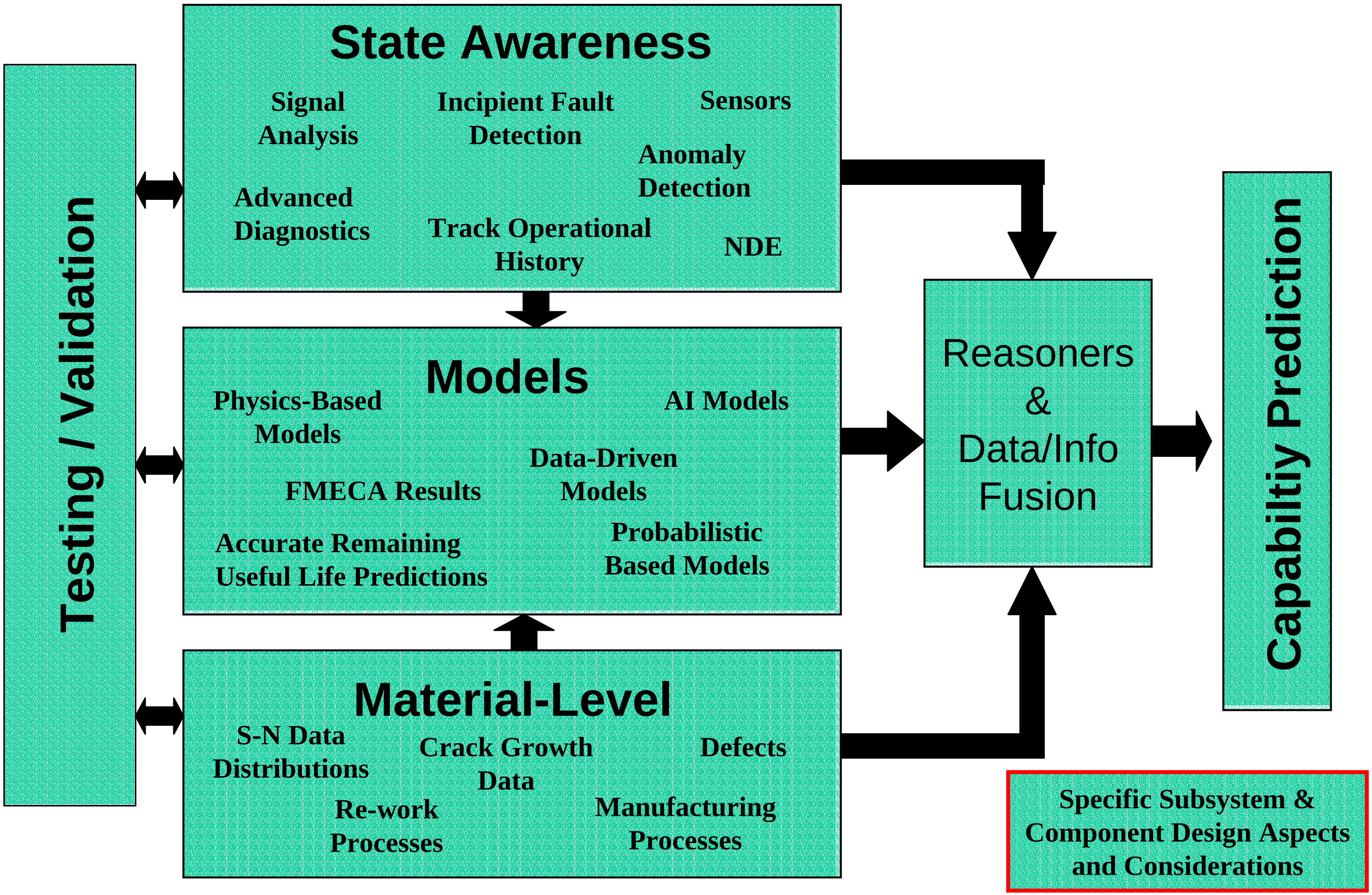
Predicting Health (Prognostics)



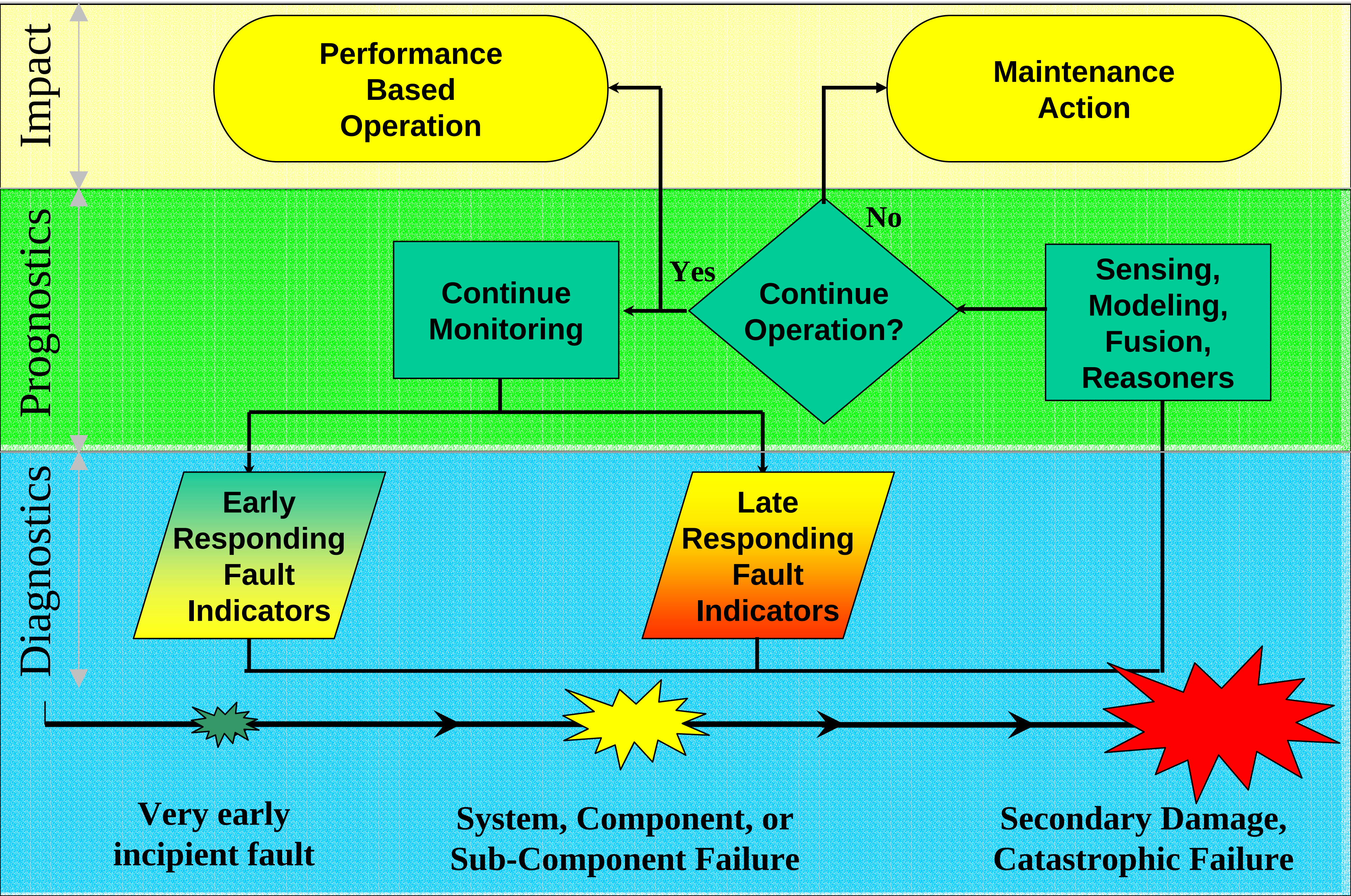
Prognostics
Tool Kit or “Bag of Tricks”

- Accurate/sensitive sensors, algorithms, indicators
- Multiple independent indicators and analysis
- Model based techniques
  - Detailed understanding of the physical system
  - Normal and degraded failure conditions
- Determination of component health at any point in time
- Incorporation of FMECA results
- Impact of secondary component damage
- Techniques for data scatter and false alarms
  - Fuzzy logic, neural networks, AI
  - Data/Information fusion
- Reasoners

Prognostics Integration Tasks



Fault Management Process and Timeline



Vibration Based Prognostics

- Using diagnostic algorithms and techniques
- Intelligent setting of alarm thresholds
  - Cockpit and maintenance
- Elimination of false alarms
- Signature deconvolution to extract incipient fault signatures and “see” precursors to component failure
- Extrapolation of diagnostic indicators and statistical data enabling trending and failure predictions
- Need to understand failure progression rates
  - Knowledge base of experienced failures
  - “Seeded fault” data base
  - Accurate models

Notional Strategy to Demo Predictive Prognostics on Helo Drivetrain

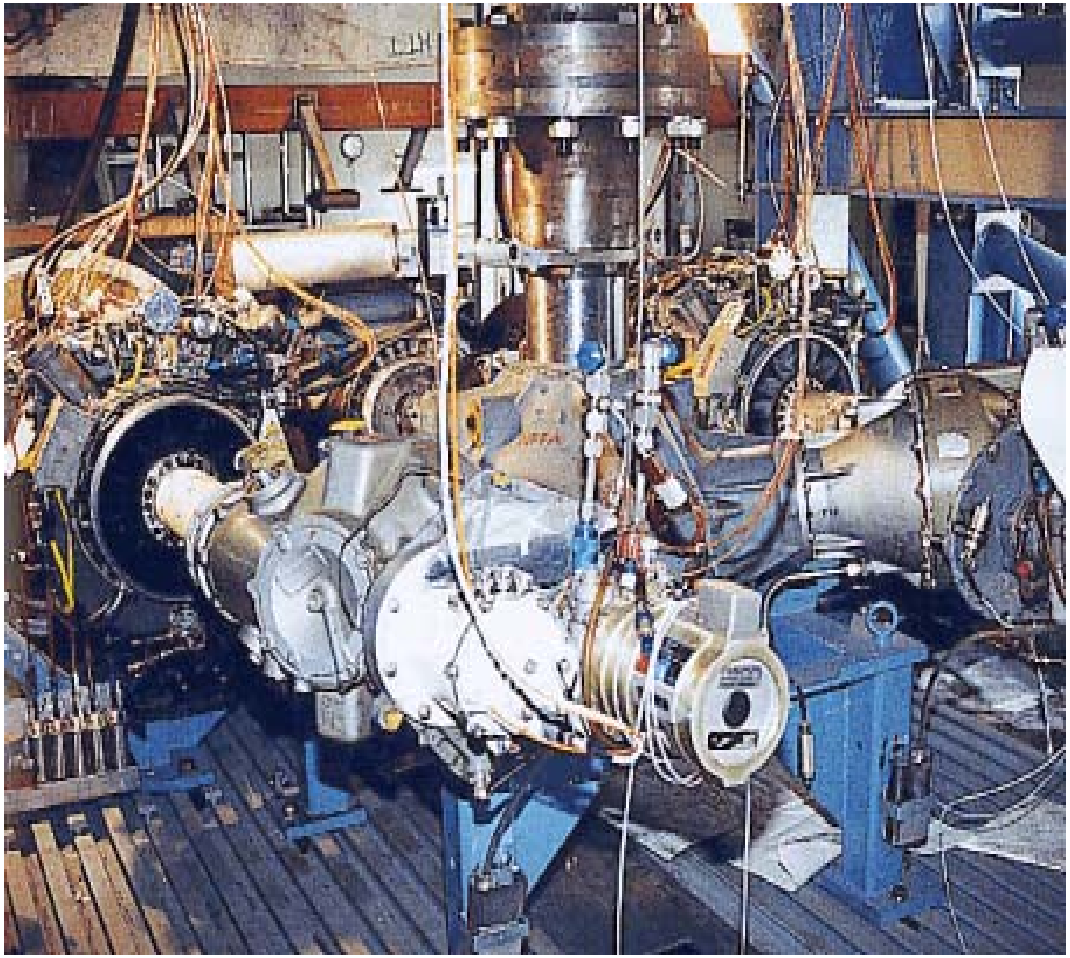
1. Identify and Target Components and Sub-elements suitable for Prognostics
   - Those with understandable fault to failure progression characteristics
   - Eliminate those impossible or too hard to consider
2. Develop and/or Obtain advanced models
   - Fault to failure progression characteristics
   - Useful life remaining
3. Perform experimental seeded fault tests
   - As many as affordable/beneficial
   - Try to understand the physics of the failure
4. Verify and validate models
   - Seeded fault and
   - Blind test data
5. Modify useful life remaining prediction model to account for real world considerations
   - Mission Profiles
   - Operational Environment
   - Operational History

PAX River
Helicopter Transmission Test Facility

SH-60 Drive System Config:
- Two T700 Engines
- Dual Engine Ops and OEI
- Main Gearbox
- Input Modules
- Accessory Modules
  - Generators
  - Hydraulic Pumps
- Tail Drive System
  - Oil Cooler, IGB, TGB, Shafting & Rotor Brake

Aircraft Loads Simulated
- Main Rotor Load - 8,000 SHP
- Main Rotor Lift - 50,000 #
- Main Rotor Bending - 5,000 #
- Tail Rotor Load - 700 SHP
- Accessories
- Rotor Brake

"Diagnostics Laboratory"



Objective

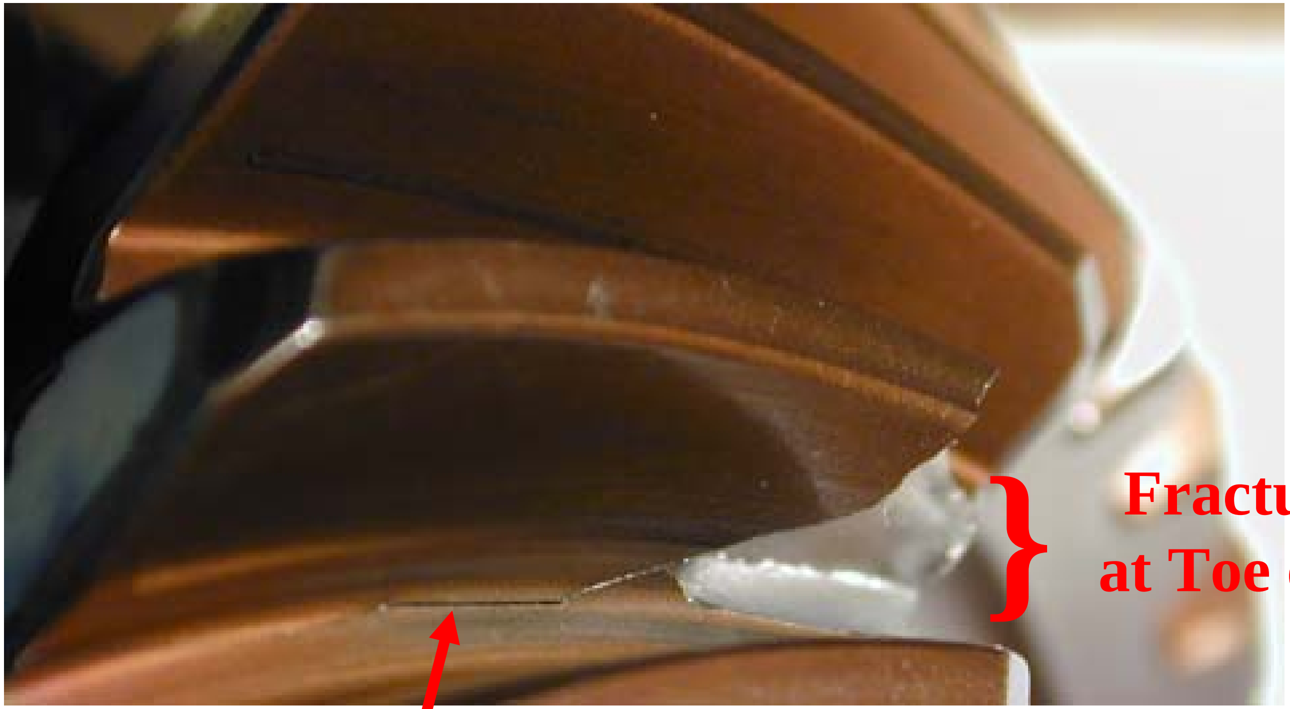
- Investigate and develop initial recommendations on integral elements for a predictive prognostic development strategy
  - Seeded fault testing
  - Physical and statistical based modeling
  - Finite element analysis
  - Material science and understanding physics of failures

- Establish baseline capability for prediction of system level useful life and performance capabilities

Procedure

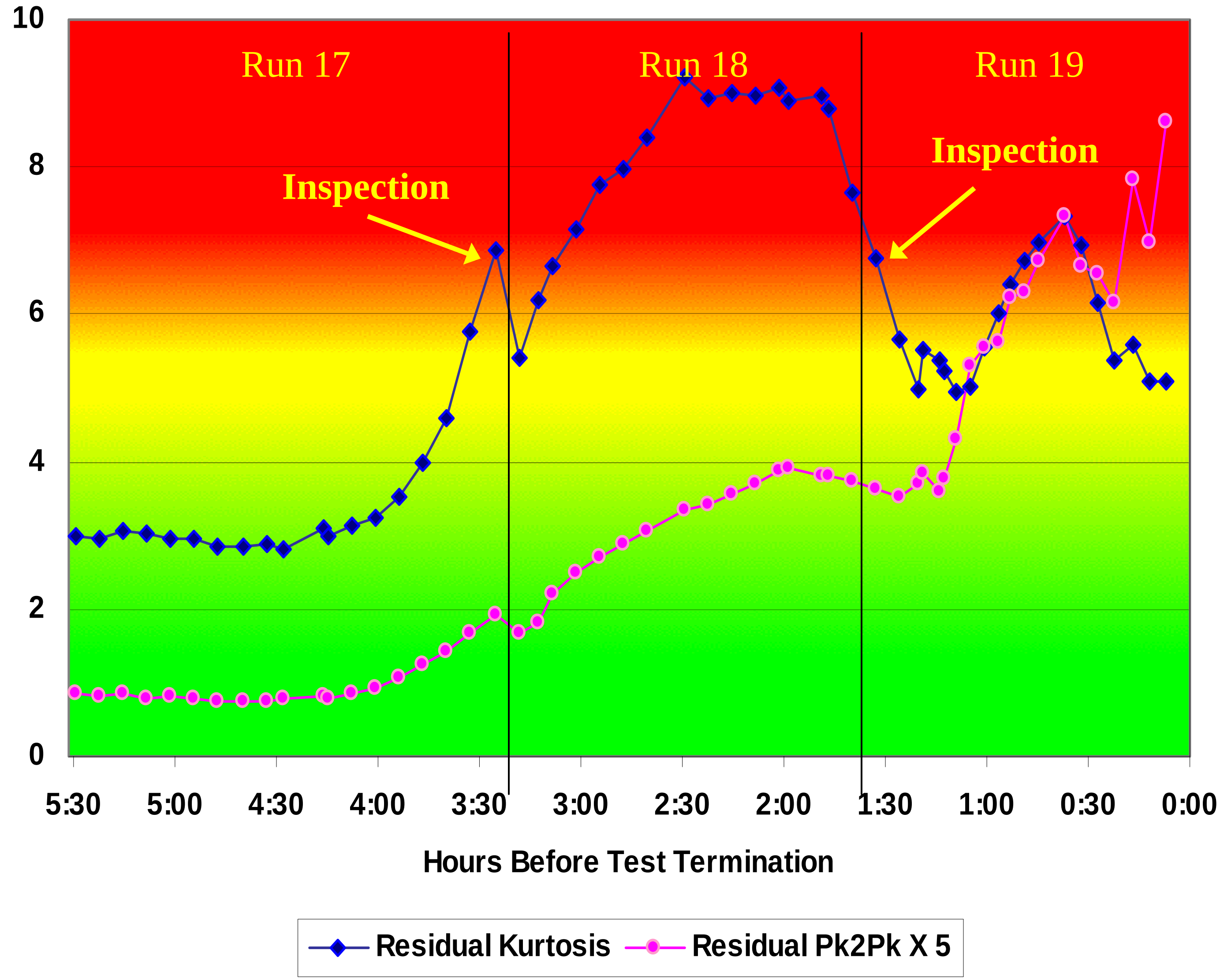
- Create stress riser in gear to induce crack
- Run gear at Pax River HTTF until just before catastrophic gearbox failure
- Inspect at regular intervals
- Attempt to:
  - Measure crack size and determine crack propagation rates
  - Predict remaining useful life
  - Obtain better understand the physics of failure for this component

IGB Crack Propagation Test

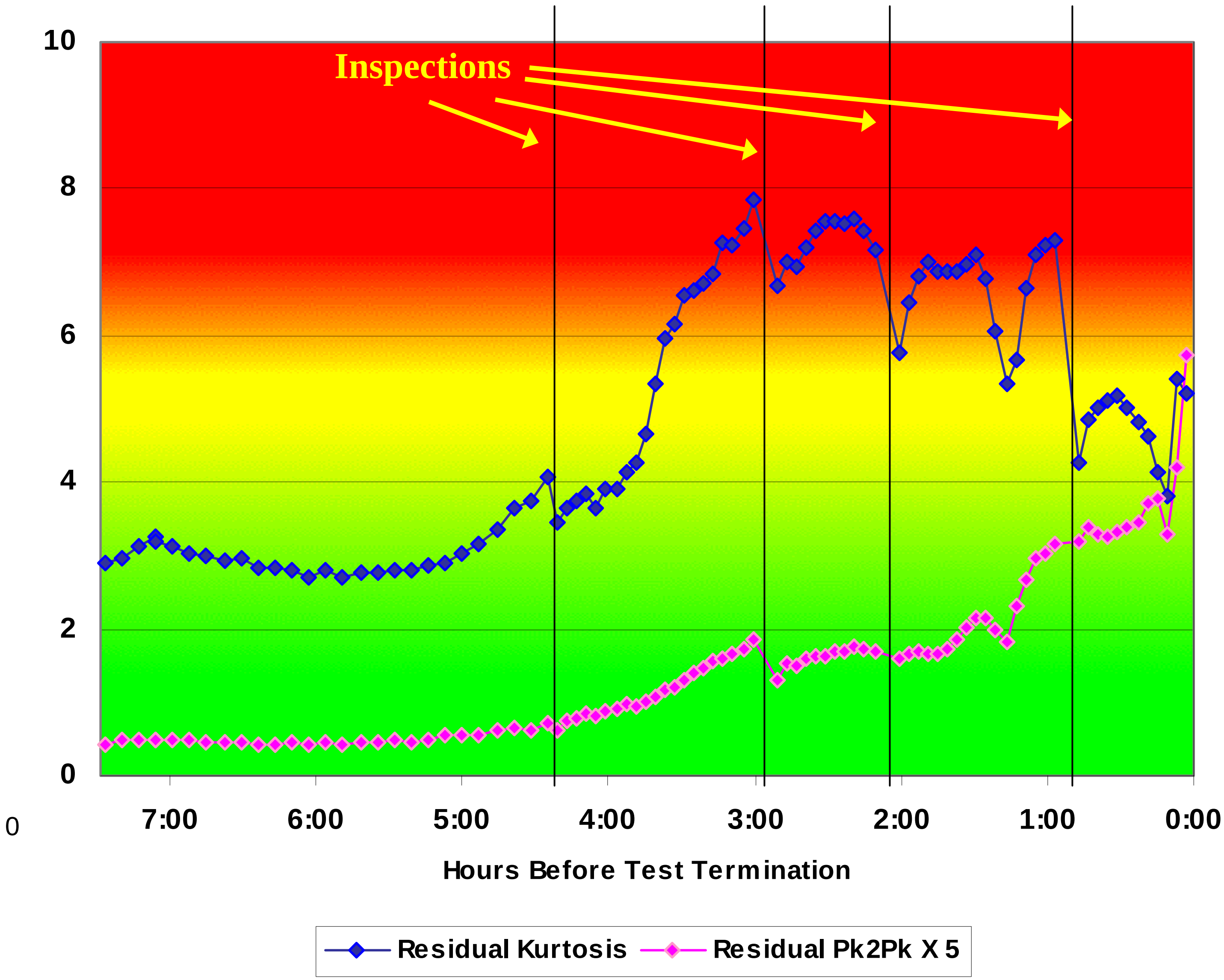


EDM Notch (0.25"L x 0.04"D x 0.005"W)

Intermediate Gearbox Pinion Crack Test
Inspections based on hours



Intermediate Gearbox Pinion Crack Test
Inspections Based on Condition Indicators



H-60 IGB Pinion Gear Surface Inspection

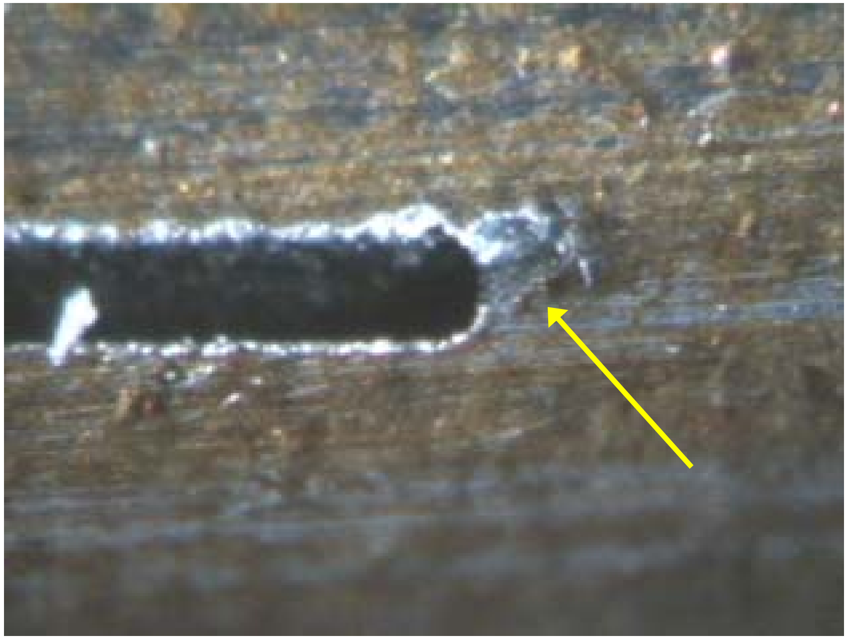
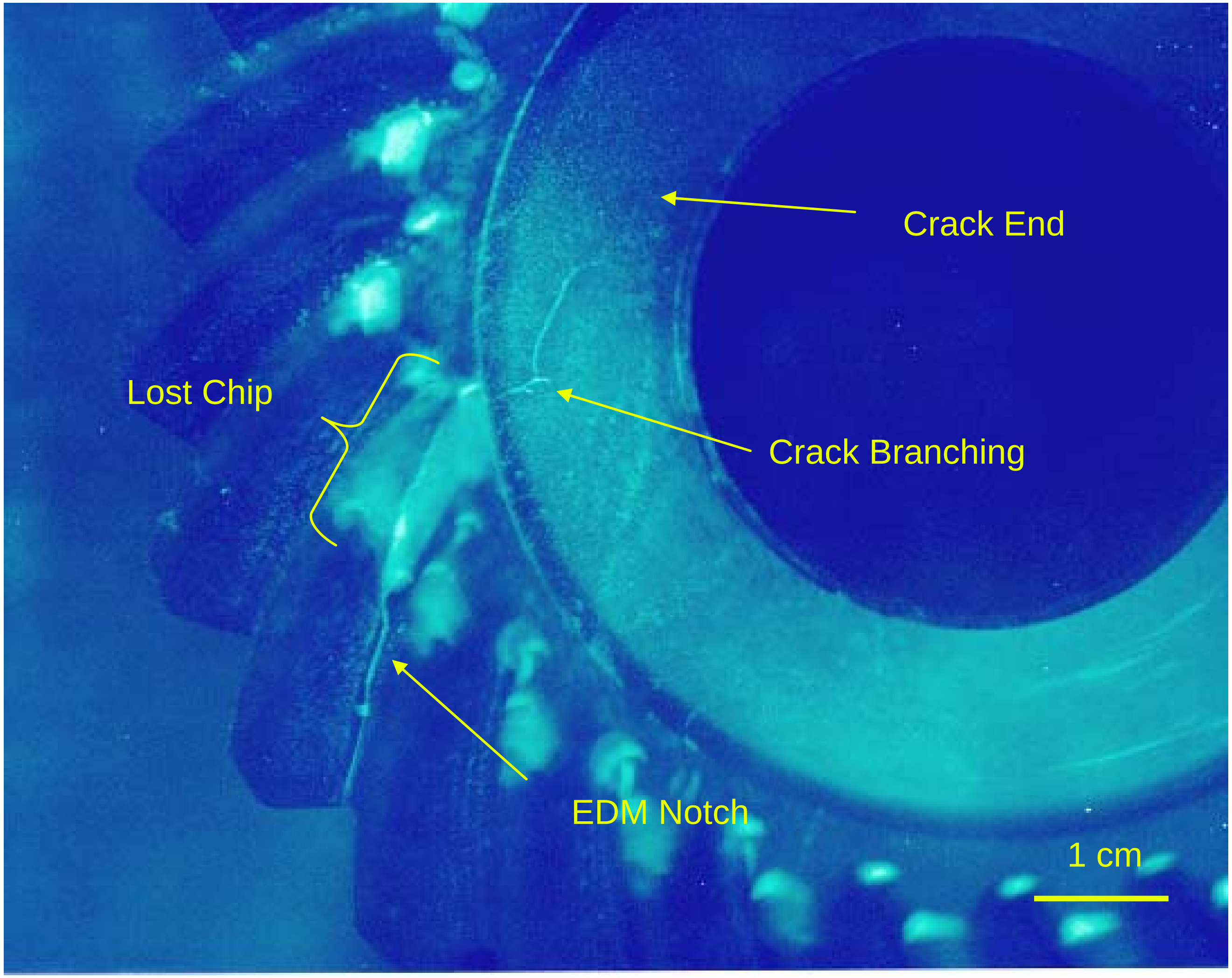


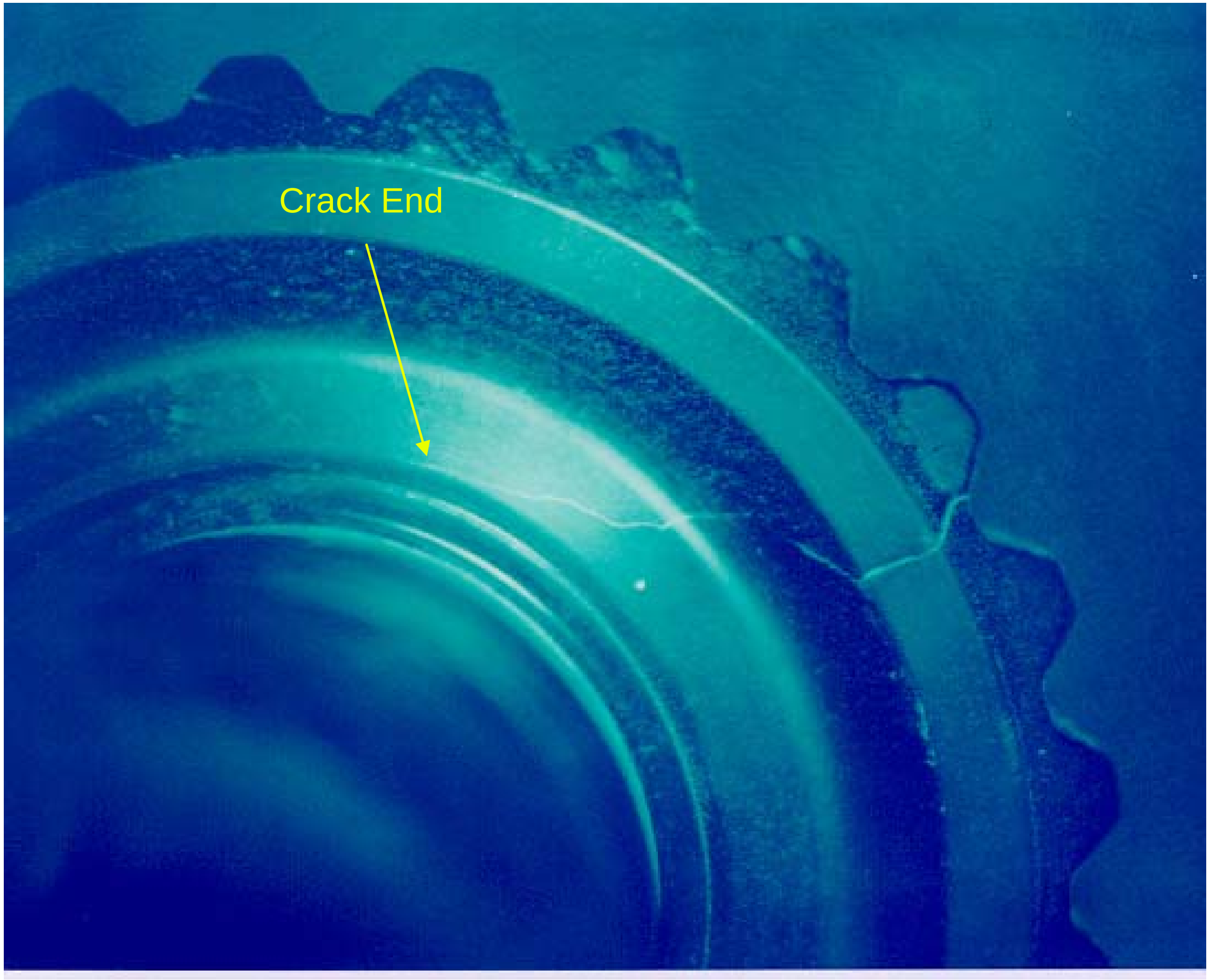
Image of heel notch inner end after Run 15 (first test), showing small chip liberated (arrow). No noticeable change until run 18.

Image of heel notch outer end after Run 18 (first test), showing obviously visible crack (arrow).

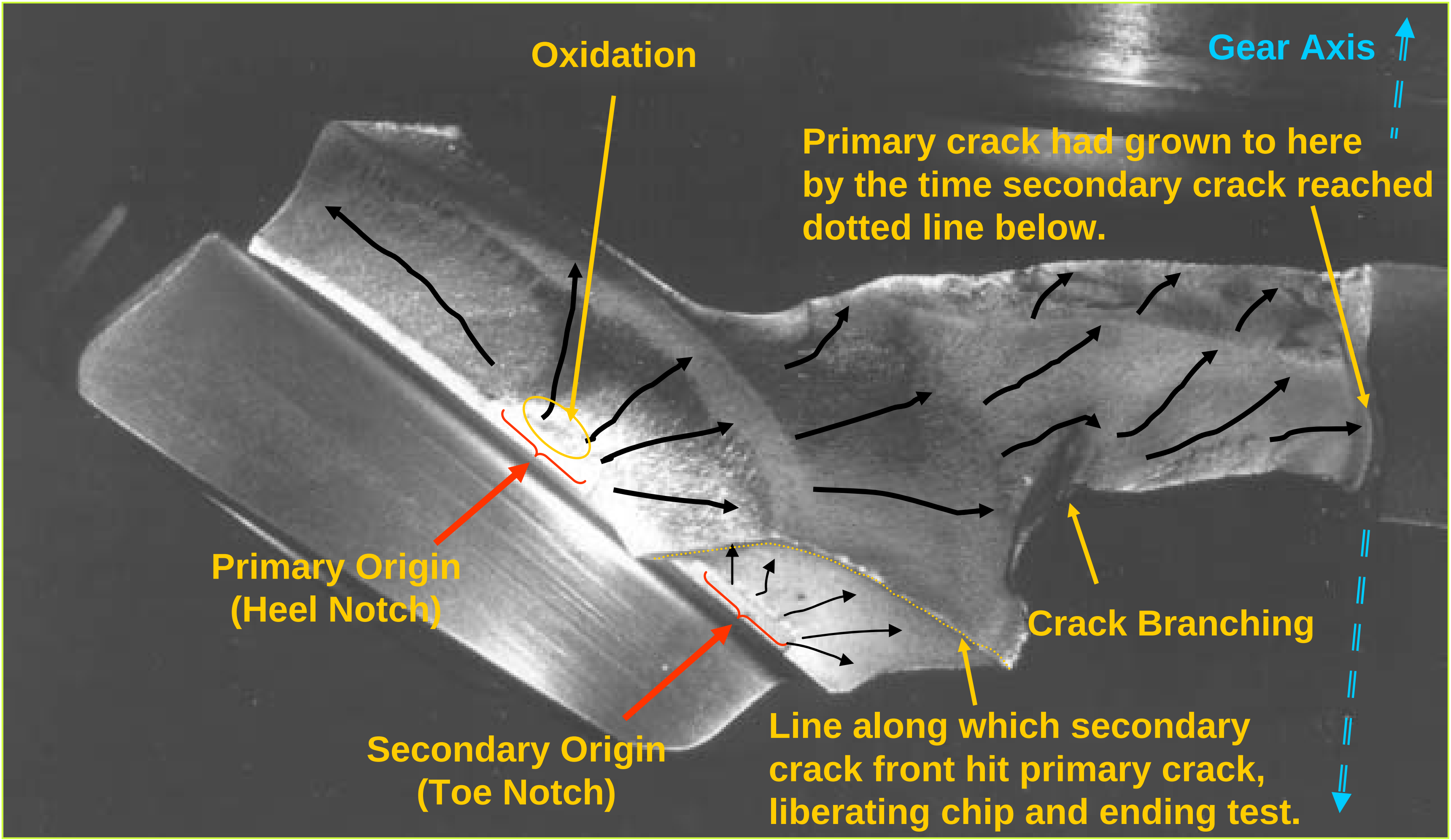
H-60 IGB Pinion Gear
Mag Particle UV Image



H-60 IGB Pinion Gear Mag Particle UV Image



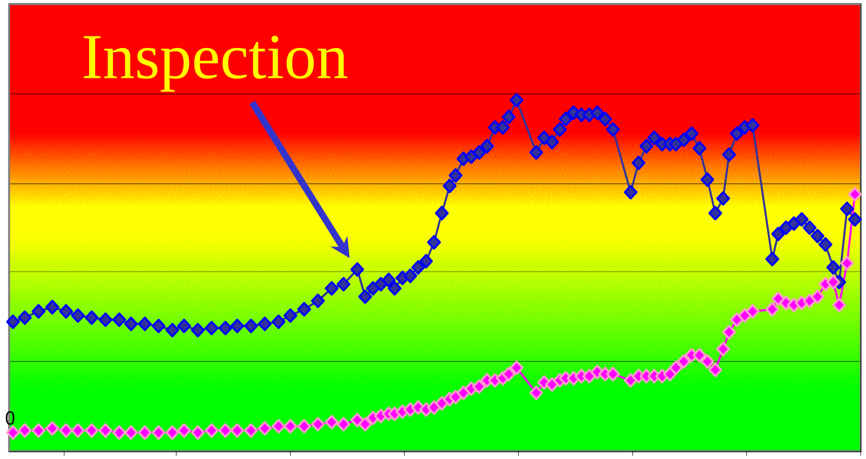
H-60 IGB Pinion Gear Fracture

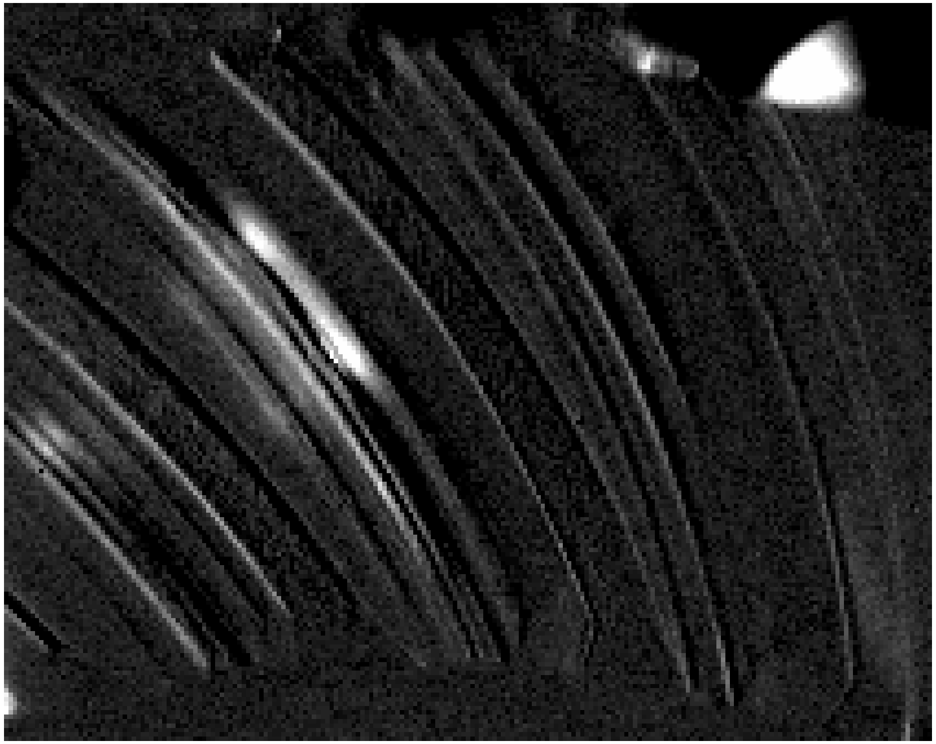


Thermosonic Imaging
Wayne State University

Second test of IGB Pinion

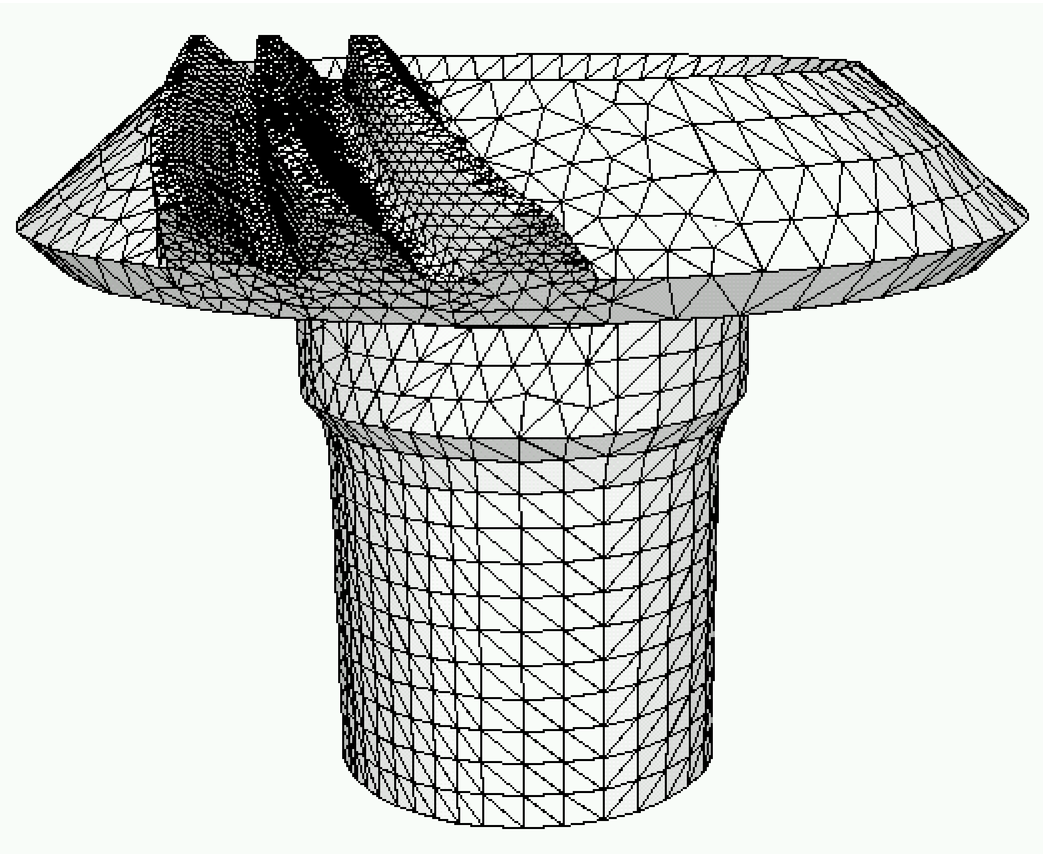
- Test Suspended upon detection of initial vibration indicator response
- Thermosonic imaging shows sub-surface crack
  - Located underneath the heel notch
  - Toe notch shows no damage



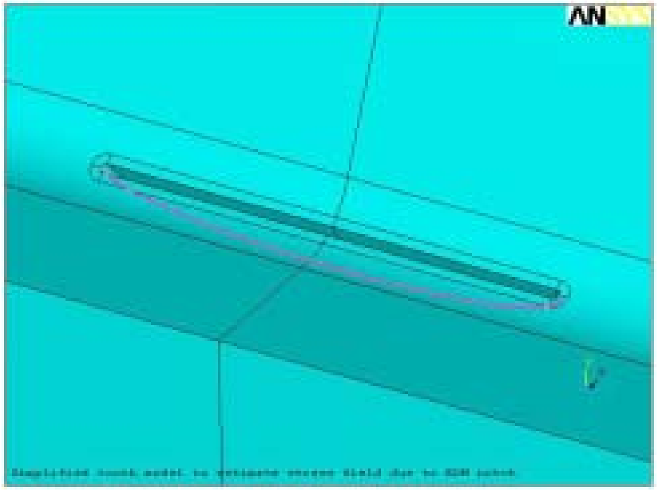


Model of the Failure
AERA and Impact SBIRs

Finite Element Mesh for IGB Pinion



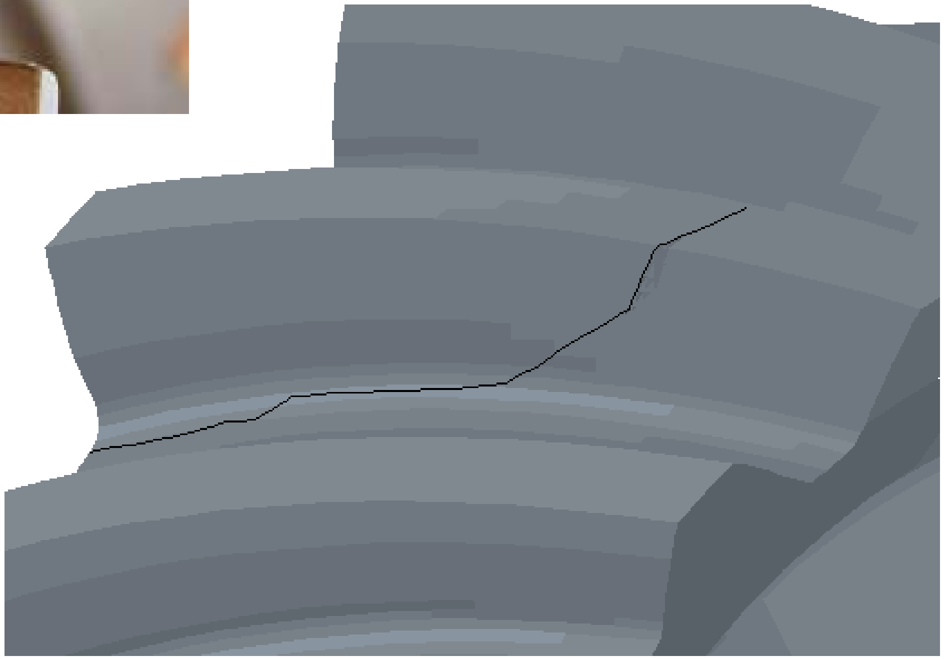
3-D Solid Model of the EDM Notch



Fracture Surface Trajectory
Actual vs Computed

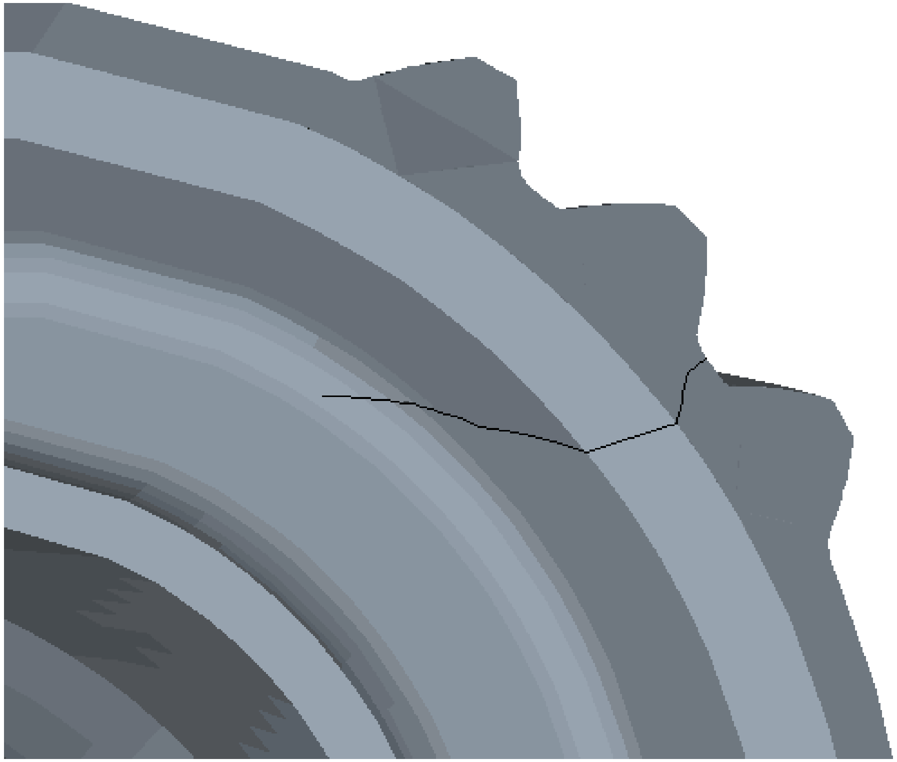
Propagation through the tooth area

FRANC3D Code used for Impact and AERA Efforts



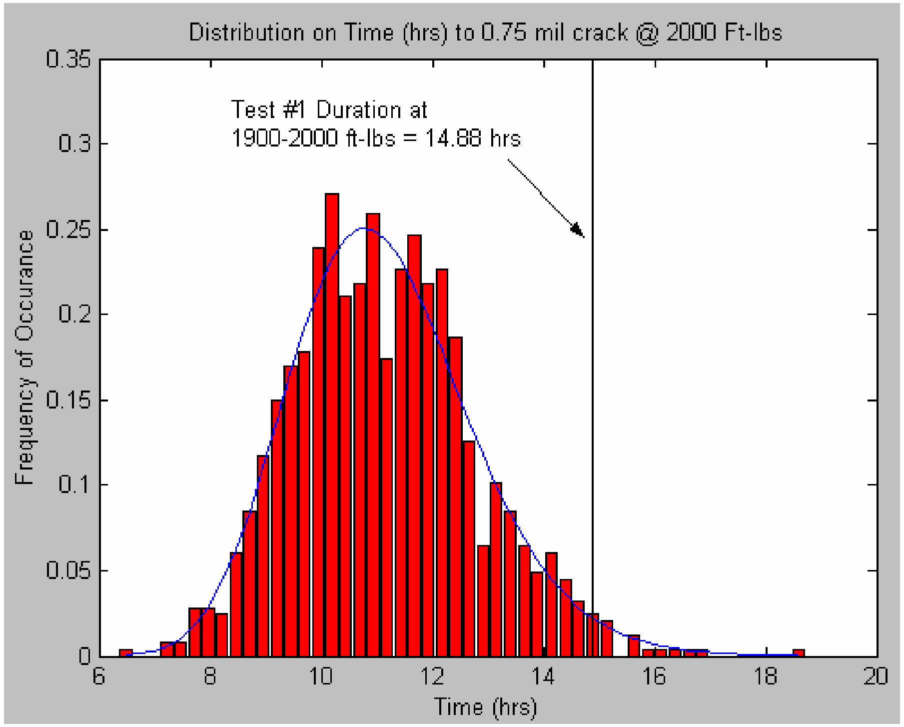
Fracture Surface Trajectory
Actual vs Computed

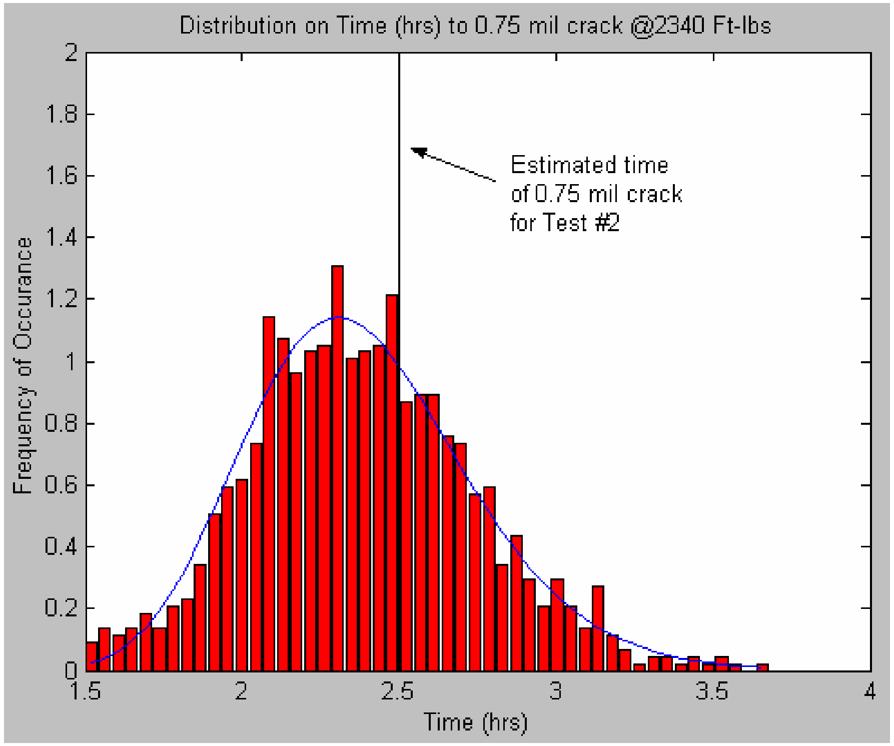
Propagation through the web area



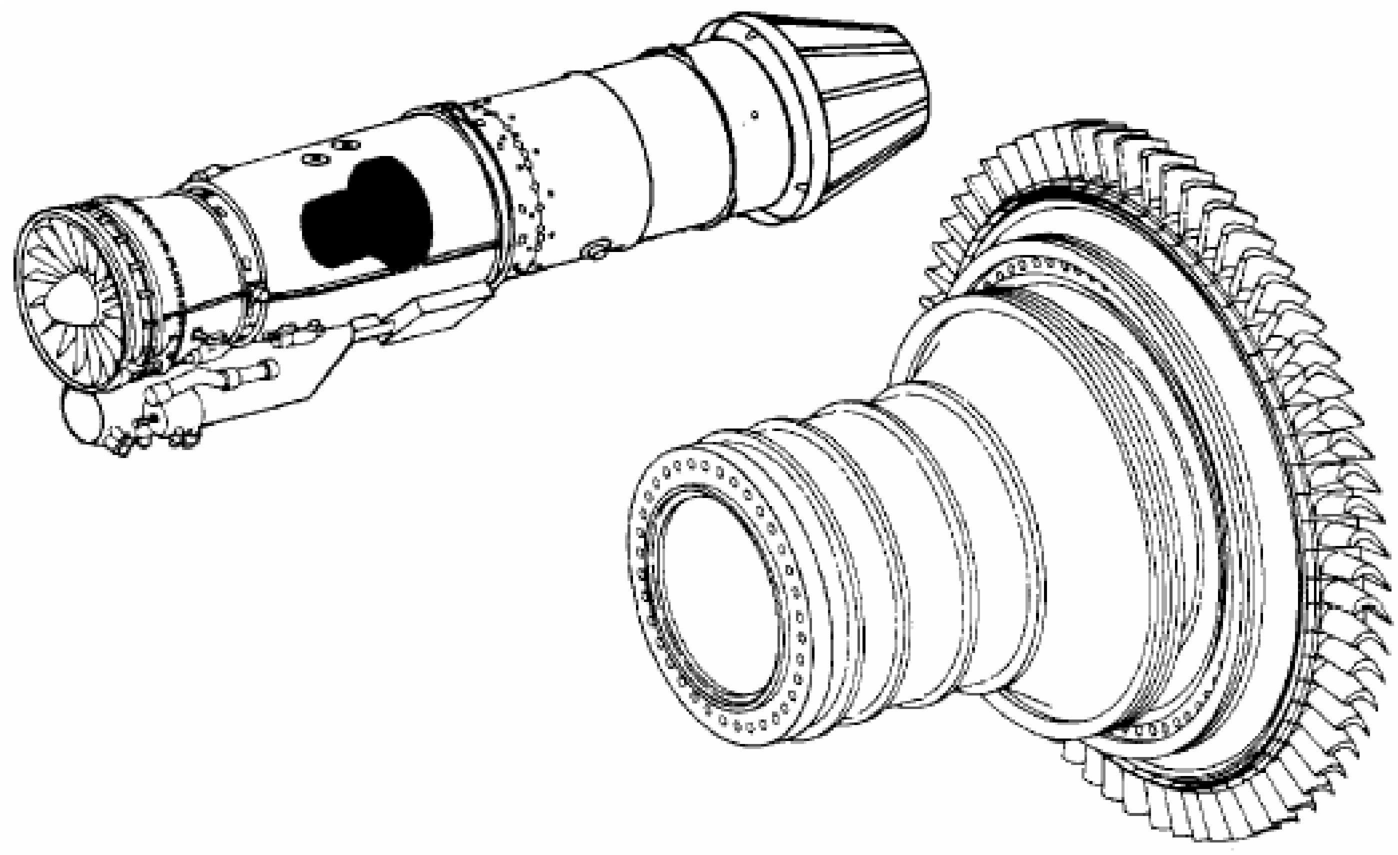
Probability of 0.75 mil Crack Impact Technologies Model

- Fractographic analysis used to estimate total run time to presence of 0.75 mil crack
- Test 1 operating profile more complex than test 2
- Model predicts 98% probability of 0.75 mil crack for test 1 and 63% probability for test 2



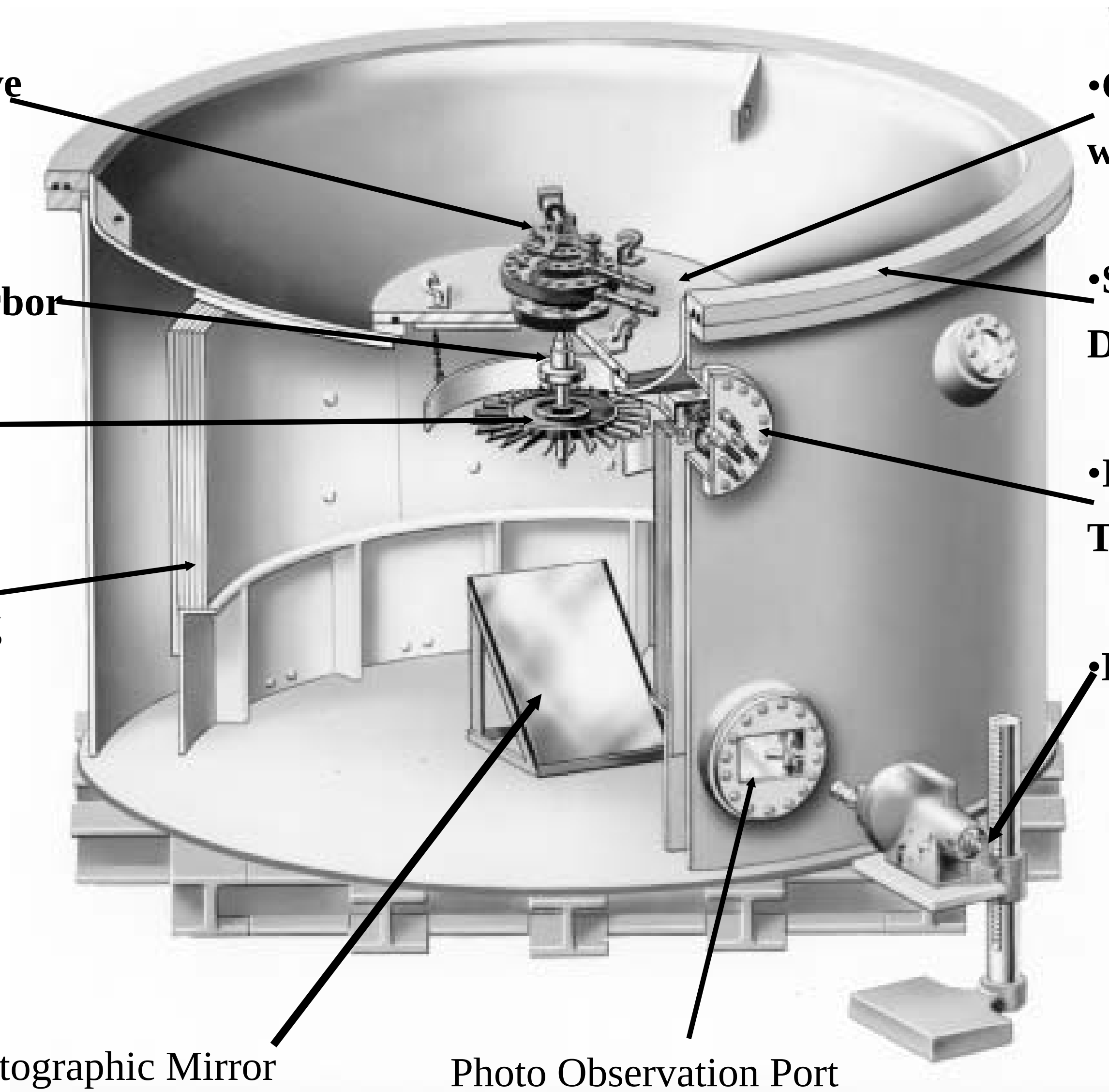


Current DARPA Program
RSF Test Article

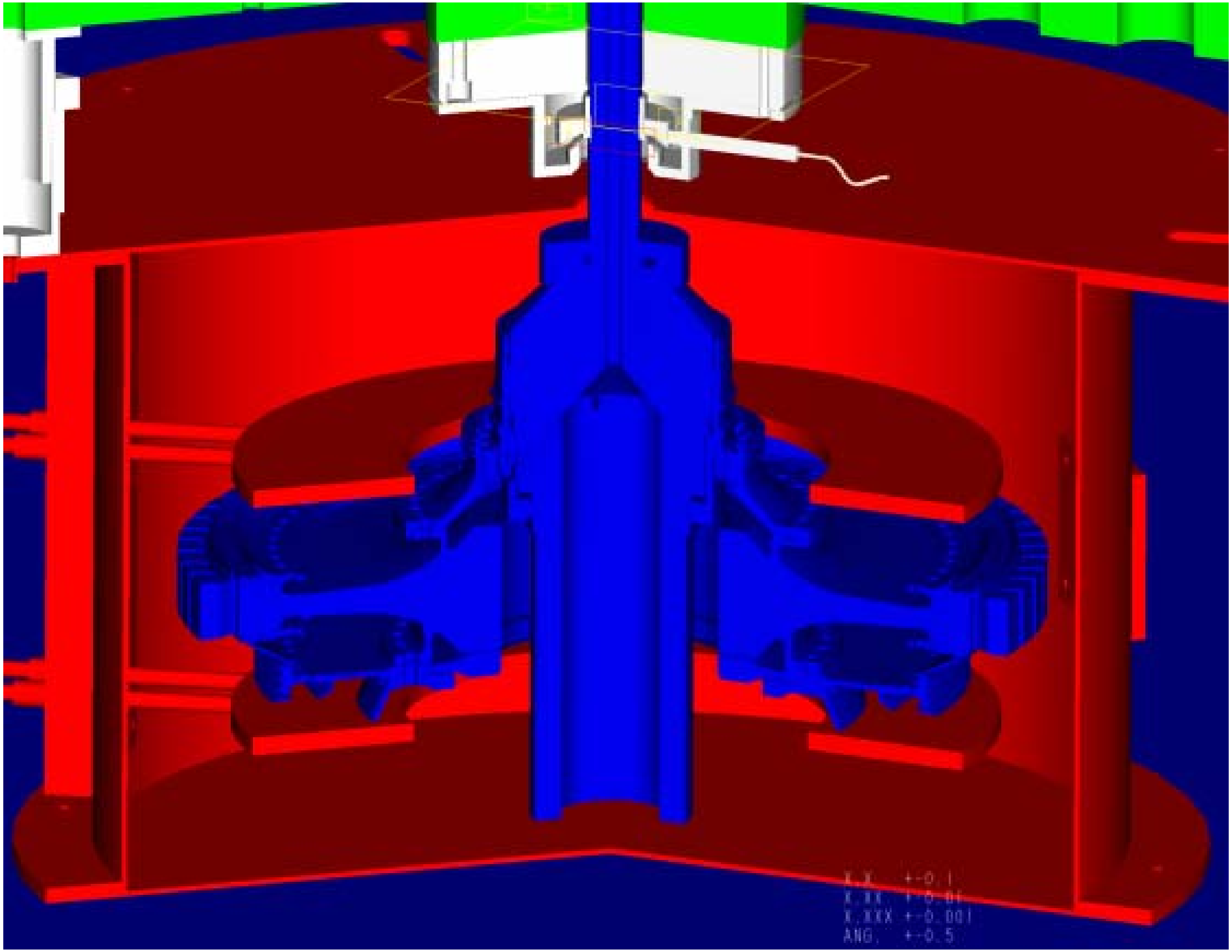


F404 High Pressure Turbine

PAX River Rotor Spin Facility
Spin Chamber Configuration



Rendering of Test Article Installed in Rotor Spin Facility



Current DARPA Program
General Overview

- Multiple failure mechanisms incorporated
  - Low Cycle Fatigue
  - Dwell
- Multiple test articles each with several flaws
- Exercise current life models
- Incorporate latest advances in modeling
- Utilize state awareness sensors to detect developing cracks
- Develop integrated models which incorporate crack detection sensor outputs to recalibrate life models
- Predict crack growth behavior as accurately as possible

Summary

- State Awareness, Modeling, Material Science/Physics, Reasoning are integral to achieving prognostics
- Initial proof of concept work demonstrates some fundamental concepts central to achieving the prognosis vision
- We are just getting started!